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Dissertation

THE USE OF A LUMMER PLATE AS AN AUXILIARY SPECTROGRAPH IN THE STUDY OF H-ALPHA OF HYDROGEN

by

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INTRODUCTION

The hydrogen lines which have been longest known are the four lying within the region of wave-lengths perceptible to the human eye as light. These are denoted by H_α, H_β, H_γ and H_δ. The first and the strongest line lies in the red, the second in the blue-green, and the third and fourth in the violet. They are commonly referred to as the Balmer series, because it was Balmer who, in 1885, made the extremely important discovery that very simple numerical relations exist between the wave-lengths of the individual lines in this series. This series has been given a complete theoretical treatment,[1] and the present quantum theory permits all the features of the hydrogen spectrum to be calculated without any approximations of a mathematical nature.

The lines of the atomic spectra of hydrogen are observed to have a fine structure. The Balmer lines of hydrogen are commonly referred to as 'doublets' and a large amount of experimental work has been done upon these doublets. The values found for the separation agree very closely with those predicted by theory.

According to the Sommerfeld formula, when the relativity correction[2] is applied and the spinning electron of Goudsmit and Uhlenbeck[3] is also used each line of the series is not only a

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[1] Sommerfeld, Atombau und Spektrallinien, P.344.

[2] Sommerfeld and Unsöld, Zeits.f.Physik, 36, 259(1926); 38, 237(1926)

[3] S.Goudsmit and G.E.Uhlenbeck, Physica, 6, 273 (1926).

doublet but is composed of five components[1]. It has been hoped that a method could be devised for showing at least a third component of a line in this series but up to the present time it has not been accomplished.

The observation and measurement of these components is extremely difficult, because the intervals between the lines are small and the components are broad. In the visible region of the spectrum, the difference in wave-length corresponding to the quantity $\Delta\nu_H$ is only about one-twentieth to one-fifth of an Ångström. Thus, in the Balmer series the lines only appear double even in spectroscopic apparatus of high resolution.

COMPREHENSIVE REVIEW OF THE WORK OF OTHER INVESTIGATORS WITH CRITICISMS

There have been about thirty papers written on the 'doublet' separation of H_α, H_β, and H_γ, but only a few experiments to verify the existence of the five components of which each of these lines are composed as predicted by the theoretical treatment. The values of the doublet separation obtained by the latest investigators of H_α agree very closely to .320 $cm.^{-1}$ as predicted by theory. This paper is not concerned with trying to improve on these values, but is concerned with the determination of the presence of a third component by means of microphotometer curves.

Curves obtained by Janicki and Lau[2] in 1925 by using a

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[1] See theory of hydrogen line H-alpha, page 5.

[2] Janicki and Lau, Zeits. f. Physik, 35, 1 (1925).

Lummer plate do not have sufficient asymmetry and also too high saddle height to show the presence of a third component. These same remarks apply to other investigators using this method until 1927, when Kent, Taylor and Pearson,[1] using two crossed Lummer plates, obtained curves with asymmetry and very little saddle height. The disadvantage here is that the curves are very ragged and irregular due to the fact that the microphotometer slit had to be very short.

The latest works on obtaining patterns to date are those of Lewis, Spedding, Shane, and Grace,[2] Williams and Gibbs[3], and W. V. Houston[4]. These investigators used the etalon and the pattern given by this interferometer is curved. With a curved pattern the resolving power of the microphotometer is less, unless the slit of the instrument is short which indeed results in an irregular microphotometer curve due to the grain of the photographic plate. This is the difficulty encountered in the crossed Lummer plate pattern obtained by Kent, Taylor and Pearson alluded to above.

REASON FOR THE STUDY OF THE H-ALPHA LINE

The primary object of this investigation is to see if a better method can be obtained for studying the H-alpha spectrum

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[1] Kent, Taylor and Pearson, <u>Phys</u>. <u>Rev</u>., <u>30</u>, 266 (1927).

[2] Lewis, G.N., and Spedding, F.H., <u>Phys</u>. <u>Rev</u>., <u>43</u>, 964 (1933).
Spedding, Shane, and Grace, <u>Phys</u>.<u>Rev</u>.,<u>44</u>,58(1933);<u>47</u>,38(1935).

[3] Williams and Gibbs, <u>Phys</u>. <u>Rev</u>., <u>45</u>, 475 (1934).

[4] Houston, W. V., <u>Phys</u>. <u>Rev</u>., <u>45</u>, 263 (1934).

by using a small Lummer plate as an auxiliary spectroscope in tandem with a larger Lummer plate, a plane reflection grating being used to separate out the H_α from the rest of the hydrogen spectrum.

PROBLEMS ENCOUNTERED

A constant deviation prism is usually used with the small Lummer plate; but it was discovered that the patterns formed consisted of curved lines which were due to the prism. When the large Lummer plate is used with this curved pattern, it gives a pattern which has lines of decreasing height and intensity. Therefore a plane reflection grating was substituted for the prism. This reduced the intensity of the light, but on the other hand gave greater dispersion.

The difficulty entering with the use of the large Lummer plate alone was that one of the two main components of the H_α doublet in a given order lies almost directly on top of the other component in an adjacent order; while if the small Lummer plate was used alone, it was difficult at liquid air temperature to get small saddle height. Hence, the small Lummer plate was used as an auxiliary spectroscope to separate these components before entering the large plate. Even this did not give the separation necessary, therefore the problem at hand was to get rid of one component of the doublet before entering the large plate by blotting it out. This problem was at first solved by the use of a shutter as outlined on pages 27-29.

ADVANTAGES OF THIS STUDY

This experiment is believed to be an improvement in the method of attack over the previous work in this field. Further, the whole spectroscopic system had a greater dispersion than instruments used by other investigators. The resolving power of the large Lummer plate, disregarding that of the small Lummer plate and grating used as auxiliary dispersion spectroscope, is practically the same as the etalon used by Houston,[1] and greater than those used by Lewis, Spedding, Shane, Grace,[2] also Williams and Gibbs[3] (See Table I, page 6). A further advantage of this experiment is that the pattern given by the system is composed of straight lines and therefore a long and narrow microphotometer slit can be used.

THEORY OF THE FINE STRUCTURE OF H-ALPHA

Sommerfeld[4] was the first to give this group of lines a complete theoretical treatment; and since then Gordon[5] and others have shown that Sommerfeld's fine structure formula may be derived from Dirac's theory of the hydrogen atom. The spinning elec-

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[1] Houston, W.V., and Hsieh, Y.M., Phys. Rev., 45, 263 (1934).

[2] Spedding, F.H., and Lewis, G.N., Phys. Rev., 43, 964 (1933).
Spedding, Shane and Grace, Phys. Rev., 47, 38 (1935).

[3] Williams, R.C., and Gibbs, R.C., Phys. Rev., 45 475 (1934).

[4] Sommerfeld, Atombau und Spektrallinien, P.344.

[5] Gordon, W., Zeits. f. Phys., 48, 11 (1928).

TABLE I

Year	Name	Instrument	Resolving Power $\lambda/\partial\lambda$
1934	Williams and Gibbs	Etalon	473,000
1934	Houston and Hsieh	Etalon	751,000
1935	Spedding, Shane and Grace	Etalon	165,000
1937	*Present Experiment	Lummer Plate	702,000

COMPARISON OF RESOLVING POWER

* Does not include the resolving power of small Lummer plate and plane reflection grating used as auxiliary spectroscope.

tron[1] and quantum mechanics[2] have introduced new corrections in the fine structure of the hydrogen line. The derivations of the formulas used are out of place here; but are taken directly from the quantum mechanics for use in the calculations in order to obtain the theoretical separations in cm.$^{-1}$ (See Fig.3).

$$\text{The main energy term } W_n = -\frac{RhcZ^2}{n^2} \qquad (7\text{-}1)$$

$$\text{Where } R = \frac{2\pi^2 m_o e^4}{ch^3} = 109737.42 \text{ cm.}^{-1}$$

(I) For the relativistic change in mass with velocity of the electron, there is given for an energy correction term[3]:

$$W_\ell = \frac{Rhca^2Z^4}{n^3}\left(3/4n - \frac{1}{L + 1/2}\right) \qquad (7\text{-}2)$$

splitting the original level of equation (7-1) into 'n' levels (s,p,d,f,......).

(II) The correction term due to the electron spin[4] is given as:

$$W_s = \frac{Rhca^2Z^4}{n^3L(L + 1/2)(L + 1)} \cdot \pm \frac{(L + 1/2) - 1/2}{2} \qquad (7\text{-}3)$$

combining equation (7-2) and (7-3) results:

$$W' = W_\ell + W_s = \frac{Rhca^2Z^4}{n^3}\left(3/4n - \frac{1}{L + 1}\right) \qquad \text{for } j = L + 1/2$$

$$W' = W_\ell + W_s = \frac{Rhca^2Z^4}{n^3}\left(3/4n - \frac{1}{L}\right) \qquad \text{for } j = L - 1/2$$

Therefore the total energy W is equal to $W_n + W'$ or

1,2,4 Heisenberg, W., and Jordon, P., Zeits. f. Phys., 37, 263 (1926).

3 Pauli, W., Zeits. f. Phys., 36, 336 (1926).

$$W = -\frac{RhcZ^2}{n^2} + \frac{Rhca^2Z^4}{n^3}(3/4n - A)$$

Where $A = \frac{1}{L+1}$ for $j = L + 1/2$ and $A = \frac{1}{L}$ for $j = L - 1/2$

As a result there are certain levels coinciding, especially those with the same values of j. On substituting the values of the constants results;

$$W = -\frac{109737.42(6.55 \times 10^{-27})(3 \times 10^{10})}{n^2} + \frac{109737.42(6.55 \times 10^{-27})(3 \times 10^{10})(5.305 \times 10^{-5})(3/4n - A)}{n^3}$$

$$W = -\frac{2.160 \times 10^{-11}}{n^2} + \frac{1.148 \times 10^{-15}}{n^3}(3/4n - A)$$

Fig. 1 page 9, shows the fine structure of H_α for the levels $n = 2$ and $n = 3$ and for the various values of A. The relativistic correction splits the term into 3 levels represented by the dashed lines $L = 0,1,2$ for $n = 3$ and into 2 levels $L = 0,1$ for $n = 2$. The magnetic effect of the spinning electron splits each of these levels, except for $L = 0$, into two and it can be shown[1] that the energy correction terms are just the right size to bring levels with the same value of j into coincidence. These have been drawn slightly separated for clearness; but actually they coincide. Because of the smallness of the separation for large values of n, only the fine structure of the level $n = 2$ has been experimentally determined for hydrogen. The frequency difference of the two spectral lines corresponding to the two

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[1] Heisenberg, W. and Jordon, P., Zeits. f. Phys., 37, 266 (1926)

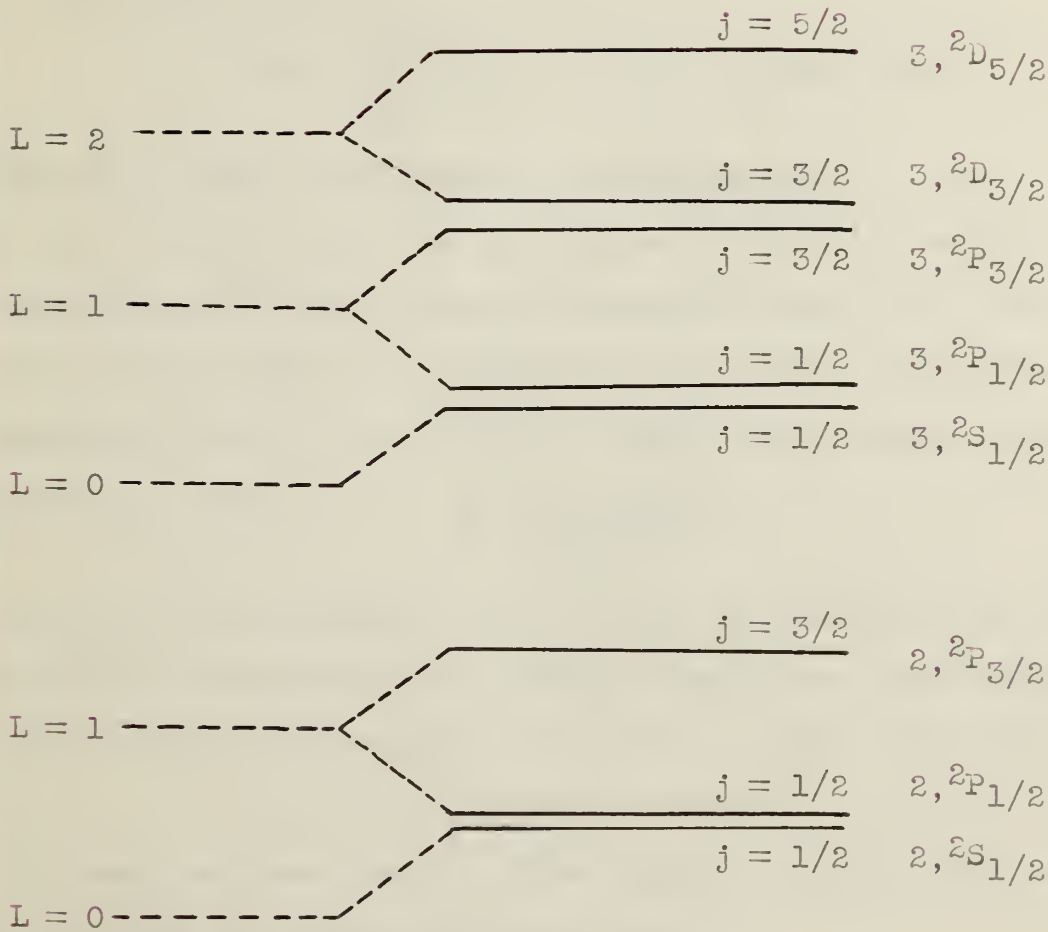

Fig. 1

Arrangement of Energy Levels.

quantum states of the hydrogen atom is known as the frequency difference of the hydrogen doublet $\Delta\nu_H$. For n = 2 this theoretical separation is

$$\Delta\nu_H = \frac{Ra^2}{n^3}(1/1 - 1/2) = 0.3645 \text{ cm}^{-1}$$

Where $a^2 = 5.305 \times 10^5$ and $R = 109737.42 \text{ cm}^{-1}$

In order to interpret the spectra we must find a set of energy levels which give the observed spectral lines, i.e., the frequency of the radiation emitted by the system when there is a transition from one state with energy W_1 to a final state of energy W_2. Thus:

$$\tilde{V} = \frac{W_1 - W_2}{h} .$$

This gives the frequency in sec^{-1}. In spectroscopy we divide this by c, the velocity of light to obtain the wave number. Therefore the 'term value' T is equal to $-W/hc \text{ cm}^{-1}$ and

$$T_2 - T_1 = \tilde{V} \text{ (in cm}^{-1})$$

The lowest and most stable state has the largest term value and thus we have the change in sign here.

CALCULATION OF T AND W FOR H-ALPHA

For n = 2 and j = 1/2, L = 0; j = 1/2, L = 1. $hc = 1.965 \times 10^{-16}$

$$W = -\frac{2.160 \times 10^{-11}}{4} + \frac{1.148 \times 10^{-15}}{8}(3/8 - 1) = -5.40 \times 10^{-12} - .898 \times 10^{-16}$$

$$T = \frac{M - .898 \times 10^{-16}}{hc} = -27500.4570 \text{ cm}^{-1} = A + .4570 \text{ cm}^{-1}$$

Where $M = -5.40 \times 10^{-12}$

" $A = -27500.$

For $n = 2$ and $j = 3/2$, $L = 1$

$$W = M - 1.436 \times 10^{-16}(3/8 - 1/2) = M - .179 \times 10^{-16}$$

$$T = \frac{M - .179 \times 10^{-16}}{1.965 \times 10^{-16}} = A + .0914 \text{ cm}^{-1}$$

For $n = 3$ and $j = 1/2$, $L = 1$; $j = 1/2$, $L = 0$

$$W = \frac{-2.160\times10^{-11}}{9} + \frac{1.148\times10^{-15}}{27}(1/4 - 1/2) = -2.40\times10^{-12} - 3.19\times10^{-17}$$

$$T = \frac{G - 3.19 \times 10^{-17}}{1.965 \times 10^{-16}} = -12210.16209 \text{ cm}^{-1} = B + .16209$$

Where $G = -2.40 \times 10^{-12}$ and $B = -12210$.

For $n = 3$ and $j = 3/2$, $L = 2$; $j = 3/2$, $L = 1$

$$W = G + 4.25 \times 10^{-17}(1/4 - 1/2) = G - 1.062 \times 10^{-17}$$

$$T = \frac{G - 1.062 \times 10^{-17}}{1.965 \times 10^{-16}} = B + .05403 \text{ cm}^{-1}$$

For $n = 3$ and $j = 5/2$, $L = 2$

$$W = G + 4.25 \times 10^{-17}(1/4 - 1/3) = G - .3550 \times 10^{-17}$$

$$T = \frac{G - .3550 \times 10^{-17}}{1.965 \times 10^{-16}} = B + .01801 \text{ cm}^{-1}$$

These calculations are tabulated in Table II, page 14.

The only possible transition of an electron from one energy state to another is given by the selection rule; i.e., j changes by 0,-1, or 1, and any violation of this rule is attributed to the presence of an external electric or magnetic field[1]. The total quantum number 'n' has no restrictions and may change by

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[1] White, Introduction to Atomic Spectra, pp. 149-170; 401-417.

any integral amount. This is represented schematically in Fig. 2, page 13, showing the spectral lines for the fine structure of H_α as predicted by the two theories.

The three original lines are from the transitions:

$2,{}^2P_{3/2}$ to $3,{}^2P_{1/2}$; $2,{}^2P_{3/2}$ to $3,{}^2D_{5/2}$; and $2,{}^2P_{1/2}$ to $3,{}^2D_{3/2}$ While the transitions on the basis of the new theory yields two new components. Thus:

$$2,{}^2P_{3/2} \text{ to } 3,{}^2D_{3/2} \text{ and } 2,{}^2S_{1/2} \text{ to } 3,{}^2S_{1/2}$$

The relative intensities[1] of the permitted transitions as predicted by wave mechanics are given by the numbers placed on the arrows. (See Fig.2, page 13.) The calculated frequencies corresponding to the possible transitions are listed in Table II, page 14. Also the relative weights of the spectral lines are listed in this Table. The difference between the center of gravity of (II+I+IV) and (III+V) is .320 cm^{-1}. The other frequency differencies are as follows:

$$(IV) - (I) = .108\ cm^{-1}$$

$$(III) - (V) = .108\ cm^{-1}$$

$$(II) - (IV) = .036\ cm^{-1}$$

These differences are shown on Fig.3, page 15. The relative height of the lines as represented in this figure correspond to the theoretical intensities as calculated by Sommerfeld and Unsöld[2] in 1926. The heavy line shows the theoretical asymmetrical curves due to the components drawn in dashed lines.

1,2 Sommerfeld and Unsöld, Zeits.f.Phys., 36, 259(1926); 38, 237('26) Also Schrödinger, E., Ann. d. Phys., 80, 437 (1926). And Ruark, A.E., and Urey, H.C., Atoms, Molecules and Quanta.

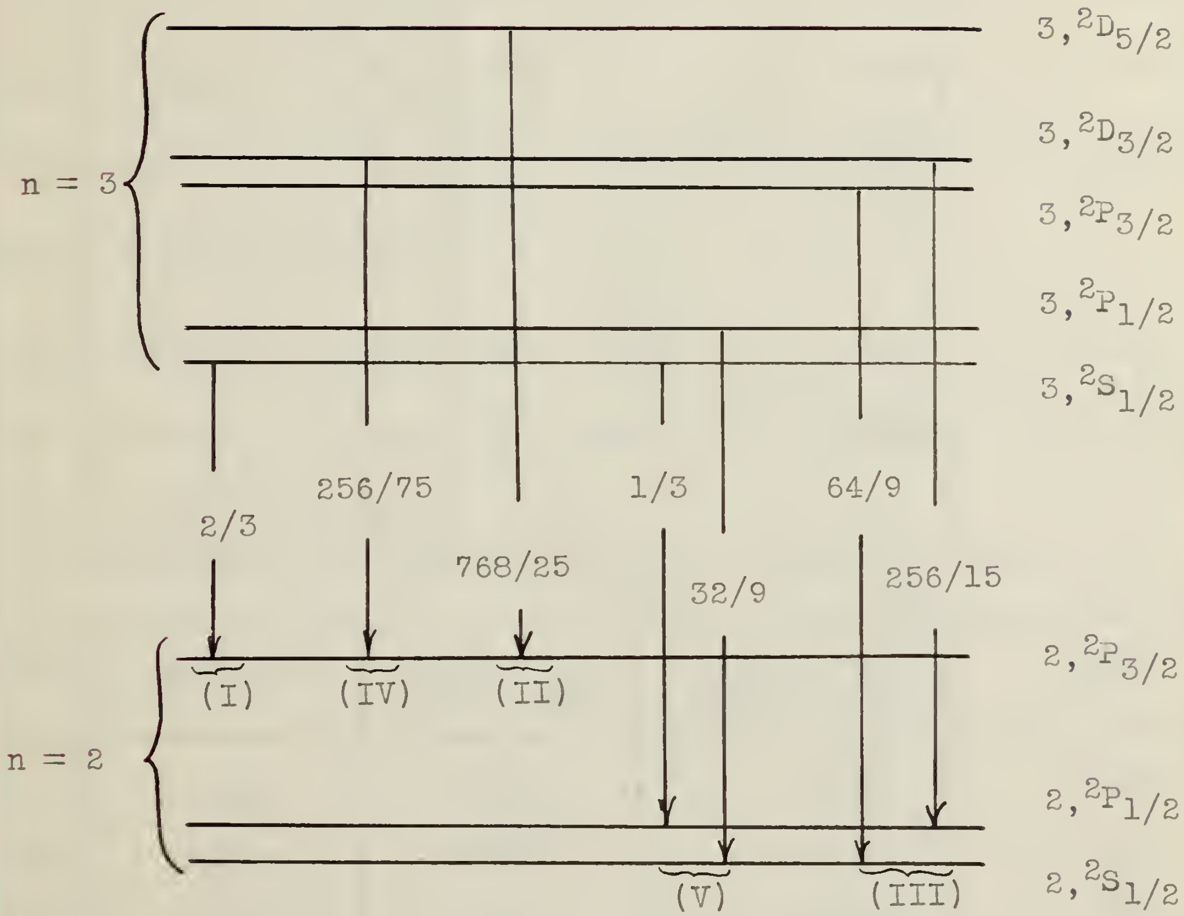


Fig. 2

SPECTRAL LINES FOR THE FINE STRUCTURE

(I),(II) and (III) are old components

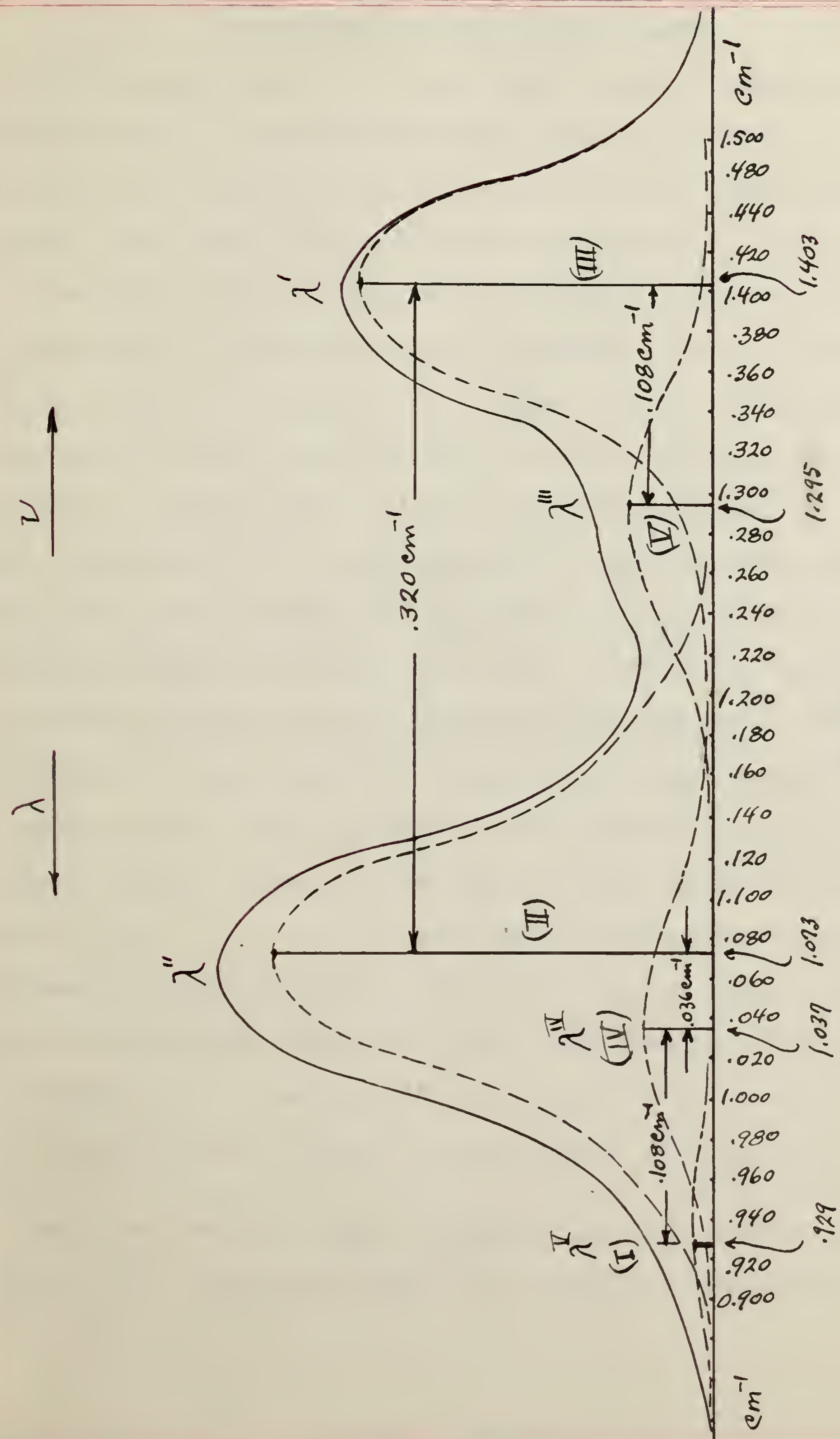
(IV) and (V) are the new components

Table II

Line	Transitions	Freq. Differences	V cm^{-1}
(I)	$3,{}^2S_{1/2} - 2,{}^2P_{3/2}$	*A + .09140 - B + .16209	*C-1 + .9293
(II)	$3,{}^2D_{5/2} - 2,{}^2P_{3/2}$	A + .09140 - B + .01801	C + .0734
(III)	$3,{}^2P_{3/2} - 2,{}^2S_{1/2}$	A + .45700 - B + .05403	C + .4029
(III)	$3,{}^2D_{3/2} - 2,{}^2P_{1/2}$	" "	"
(IV)	$3,{}^2D_{3/2} - 2,{}^2P_{3/2}$	A + .09140 - B + .05403	C + .0374
(V)	$3,{}^2P_{1/2} - 2,{}^2S_{1/2}$	A + .45700 - B + .16209	C + .20491
(V)	$3,{}^2S_{1/2} -2, {}^2P_{1/2}$	" "	"

Line	Intensity	Approx. freq. cm^{-1}	Intensity x Approx. Freq.	Wgts.
(I)	2/3	0.929	0.618	0.667
(II)	768/25	1.073	32.963	30.720
(III) (III)	1088/45	1.403	33.921	24.178
(IV)	256/75	1.037	3.540	3.413
(V) (V)	35/9	1.295	5.036	3.889

*Note: A = -27500.; B = -12210.; C = 15290.



λ
ν
λ'
λ''
λ'''
λ^IV
λ^V
(I)
(II)
(III)
(IV)
(V)
.320 cm^-1
.108 cm^-1
.108 cm^-1
.036 cm^-1
cm^-1
cm^-1
1.500
.480
.440
.420
1.403
1.400
.380
.360
.340
.320
1.300
1.295
.280
.260
.240
.220
1.200
.180
.160
.140
.120
1.100
.080
1.073
.060
.040
1.039
.020
1.000
.980
.960
.940
.929
.920
0.900

Fig. 3.
λ6563 Å

THE THEORY OF THE LUMMER PLATE

The Lummer plate is an extremely ingenious device for obtaining narrow interference fringes under conditions of large retardation of path, and was originated by O. Lummer and E. Gehrke[1]. The light from the radiating source is made parallel by a lens and enters a long slab of plane-parallel glass at such an angle that it meets the second surface at very nearly the critical angle. To prevent the large loss by reflection at the first surface which would occur at the very oblique incidence necessary, a small prism P (See Fig.4) is cemented to one surface. Because of the large angle of incidence only a small portion of the energy escapes along path '1', the remainder being reflected to-and-fro within the plate. After two internal reflections a second portion emerges along path '2'. The path-difference between these two rays is now very large, being equal to $\mu(BA + AC) - BA$. Due to the small amount of energy which escapes at each reflection we have a large number of parallel beams, 1,2,3,...........n, with path differences increasing in arithmetical progression[2] on each side of the plate. If the successive emergent beams '1', '2', etc., which are parallel, are brought to a common focus by an objective 'O', the beams will reinforce and produce bright fringes forming the patterns

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[1] Lummer and Gehrcke, Ann. d. Physik, 10, 457 (1903).

[2] Wood, R. W., Physical Optics, pp. 282-287, 2nd Edition (1929).

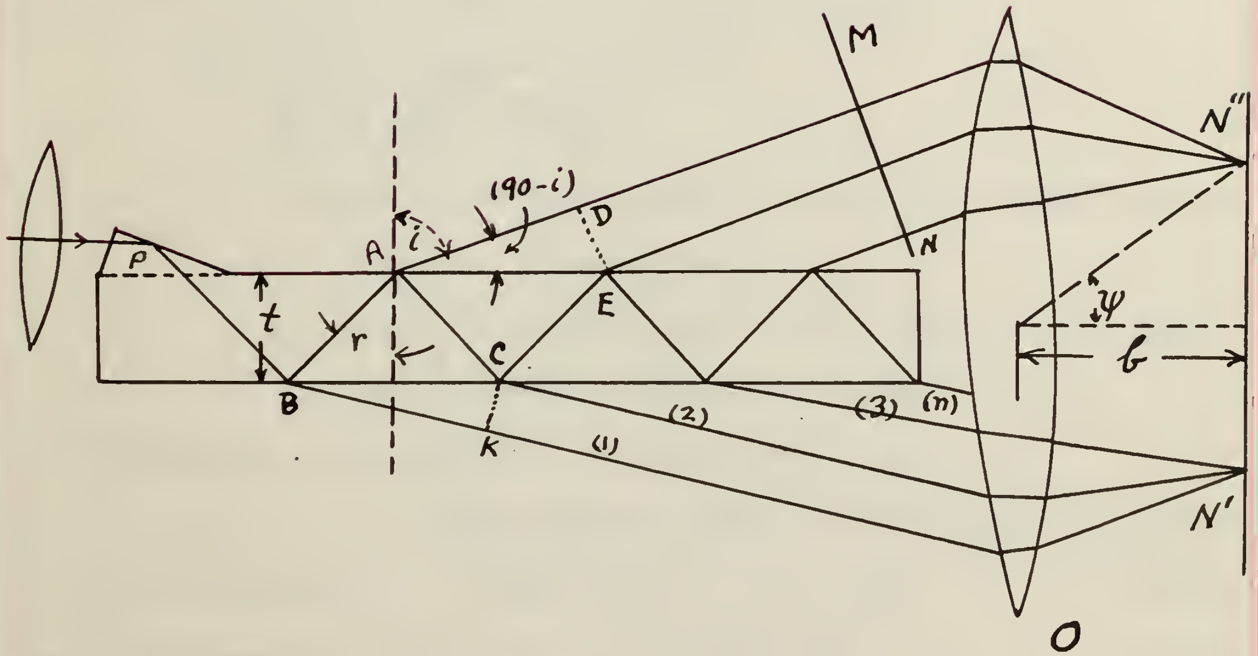

Fig. 4

FORMATION OF LUMMER PLATE FRINGES-TOP VIEW

N' on one side of the plate or N" on the other side. The two sets are identical and not complementary; but the pattern is made up of straight lines. As used in this investigation the plate is set on edge and disperses horizontally. This is shown in Fig.4.

SEPARATION BETWEEN ORDERS

The development of these equations is taken from Williams[1] and Wood[2] with slight alterations by the writer.

Let t = thickness of plate
μ = refractive index
λ = a wave length

i = angle between normal to the side of the plate and the emergent beam

r = angle between normal to the side of the plate and the beam within the glass

The fundamental condition for reinforcement is:

$$2\mu t\cos(r) = n\lambda \quad \text{(See Fig.4)} \qquad (18\text{-}1)$$

If $\sin(i) = \mu\sin(r)$ Then $\sin(r) = \sin(i)/\mu$ (18-2)

From trigonometry $\cos(r) = (1 - \sin^2(r))^{1/2}$ (18-3)

Substituting from equation (18-2) in (18-3)

$$\cos(r) = 1/\mu(\mu^2 - \sin^2(i))^{1/2} \qquad (18\text{-}4)$$

Substituting (18-4) in (18-1)

$$2t(\mu^2 - \sin^2(i))^{1/2} = n\lambda \qquad (18\text{-}5)$$

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[1] Williams, Application of Interferometry, pp. 95-103 (1930).

[2] Wood, R. W., Physical Optics, pp. 282-287, 2nd Edition (1929).

$$\text{Where } \lambda = \frac{2t(\mu^2 - \sin^2(i))^{1/2}}{n}$$

Squaring $\lambda^2 = \dfrac{4t^2(\mu^2 - \sin^2(i))}{n^2}$ or $\lambda = \dfrac{4t^2(\mu^2 - \sin^2(i))}{n^2}$ (19-1)

$$\lambda^2 n^2 = 4t^2\mu^2 - 4t^2\sin^2(i) \qquad (19\text{-}2)$$

Differentiating (19-2) with i and n as variables

$$2n\,\lambda^2\Delta n = -8t^2\sin(i)\cos(i)\,\Delta i \qquad (19\text{-}3)$$

But from trigonometry $\sin(2i)/2 = \sin(i)\cos(i)$ (19-4)

Substituting (19-4) in (19-3) results:

$$-2t^2\sin(2i)\,\Delta i = n\,\lambda^2\Delta n$$

and solving for Δi

$$\Delta i = -\frac{n\,\lambda^2}{2t^2\sin(2i)}\cdot\Delta n \qquad (19\text{-}5)$$

Putting $\Delta n = 1$ and the value of λ from equation (18-5) in equation (19-5) results in:

$$\Delta i = \frac{-n\lambda^2}{2t^2\sin(2i)} = -\frac{n\,\lambda\,2t(\mu^2-\sin^2(i))^{1/2}}{n2t^2\sin(2i)} = -\frac{\lambda(\mu^2-\sin^2(i))^{1/2}}{t\,\sin(2i)}$$

(19-6)

Therefore equation (19-6) is the angle between successive orders. Δi represents this angle and is independent of the length of the plate, increases with wave-length and approaches grazing emergence. It also varies inversely as the thickness of the plate.

DISPERSION

Differentiating equation (19-2) with respect to 'λ' and considering the refractive index 'μ' also as a variable:

$$8t^2\mu\frac{\partial\mu}{\partial\lambda} - 8t^2\sin(i)\cos(i)\frac{\partial i}{\partial\lambda} = 2n^2\,\frac{\cancel{\partial\lambda}}{\cancel{\partial\lambda}} \qquad (20\text{-}1)$$

$$4t^2\mu\frac{\partial\mu}{\partial\lambda} - 2t^2\sin(2i)\frac{\partial i}{\partial\lambda} = n^2\lambda \qquad (20\text{-}2)$$

Solving (20-2) for $\frac{\partial i}{\partial\lambda}$ results:

$$\frac{\partial i}{\partial\lambda} = \frac{4t^2\mu\frac{\partial\mu}{\partial\lambda} - n^2\lambda}{2t^2\sin(2i)} \qquad (20\text{-}3)$$

Substituting λ from equation (19-1) in (20-3)

$$\frac{\partial i}{\partial\lambda} = \frac{4t^2\mu\frac{\partial\mu}{\partial\lambda} - n^2\left[\frac{4t^2(\mu^2 - \sin^2(i))}{n^2}\right]}{2t^2\sin(2i)}$$

$$\frac{\partial i}{\partial\lambda} = \frac{4t^2\lambda\mu\frac{\partial\mu}{\partial\lambda} - 4t^2(\mu^2 - \sin^2(i))}{2t^2\lambda\sin(2i)}$$

$$\frac{\partial i}{\partial\lambda} = \frac{2\lambda\mu\frac{\partial\mu}{\partial\lambda} - 2(\mu^2 - \sin^2(i))}{\lambda\sin(2i)} \qquad (20\text{-}4)$$

Equation (20-4) is the dispersion which is shown to be independent of the size and shape of the plate. It depends only upon the optical properties of the plate 'μ', the wave-length 'λ' and the angle of emergence.

RESOLVING POWER

If Δi in equation (19-6) and Δi in equation (20-3) are set equal to each other, we then can solve for $\Delta\lambda$, the range of the plate without overlap, i.e., to say $\Delta\lambda$ is the difference of the wave-length which a component line in any order must have so that it coincides with the main fringe of the next order.

From equation (20-3) $\Delta i = \dfrac{4t^2\mu\frac{\partial\mu}{\partial\lambda} - n^2\lambda}{2t^2\sin(2i)} \times \Delta\lambda$

From equation (19-6) $\Delta i = -\dfrac{n\,\lambda^2}{2t^2 \sin(2i)}$

$$\text{or}\quad \frac{4t^2\mu\frac{\partial\mu}{\partial\lambda} - n^2\lambda}{2t^2\sin(2i)}\cdot\Delta\lambda = -\frac{n\lambda^2}{2t^2\sin(2i)}$$

Solving for $\Delta\lambda$:

$$\Delta\lambda = \frac{-n\,\lambda^2(2t^2\sin(2i))}{(2t^2\sin(2i))\left[4t^2\mu\frac{\partial\mu}{\partial\lambda} - n^2\right]}$$

$$\Delta\lambda = \frac{n\,\lambda^2}{n^2\lambda - 4t^2\mu\frac{\partial\mu}{\partial\lambda}} \qquad (21\text{-}1)$$

Equation (21-1) gives the range of the plate without overlap, that is, the difference between the component line and the main fringe of the next order. In Fig.4, if MN be the wave front and the width of the beam entering the telescope lens '0' then, ANcos(i) = L cos(i). Where L is the length of the plate, the angle Δi between the central maximum and the first minimum for a beam of this width is:

$$\Delta i = \frac{\lambda}{L\cos(i)} \qquad (21\text{-}2)$$

Rearranging equation (21-1) and substituting (19-4) gives:

$$\partial i = \frac{2\lambda\mu\frac{\partial\mu}{\partial\lambda} - 2\mu^2 + 2\sin^2(i)}{\lambda 2\cdot\cos(i)\sin(i)} \times \partial\lambda = \frac{\lambda\mu\frac{\partial\mu}{\partial\lambda} - \mu^2 + \sin^2(i)}{\lambda\cos(i)\sin(i)} \times \partial\lambda$$

$$\partial i = -\frac{1}{\sin(i)\cos(i)}\left\{\mu^2 - \sin^2(i) - \lambda\mu\frac{\partial\mu}{\partial\lambda}\right\}\partial\lambda \qquad (21\text{-}3)$$

Substituting Δi from equation (21-2) in (21-3)

$$\frac{\lambda}{L\cos(i)} = \frac{1}{\lambda\cos(i)\sin(i)}\left\{\mu^2 - \sin^2(i) - \lambda\mu\frac{\partial\mu}{\partial\lambda}\right\}\partial\lambda$$

Therefore $\dfrac{\lambda}{\partial\lambda} = \dfrac{L}{\lambda\sin(i)}\left\{\mu^2 - \sin^2(i) - \lambda\mu\dfrac{\partial\mu}{\partial\lambda}\right\}$ is the resolving power of the Lummer plate. However, this is only true at grazing emergence, since $\partial i = \lambda/L\cos(i)$, that is, only when the amplitude is uniform over the wave front MN. The resolving power of the large Lummer plate is given in Table I, page 6.

DESCRIPTION OF APPARATUS

Source of Radiation

It was necessary to use a source which would produce the Balmer lines with the greatest possible intensity relative to the secondary spectrum and which would give the narrowest possible lines. The first requirement was met by the use of a Wood[1] tube, while the second was attained by cooling the capillary by liquid air.

The Wood tube was of pyrex glass 36 cm long (See Fig.5) and 1 cm in diameter. The discharge was maintained by a transformer with 30,000 volts on the secondary or at the terminals of the tube. Hydrogen was formed by the electrolytic process and admitted to the tube through stop-cocks. The correct pressure in the tube was obtained by means of a Hyvac pump and measured by a McLeod gauge.

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[1] Wood, R.W., Proc. Roy. Soc. London, A 97, 455 (1920).

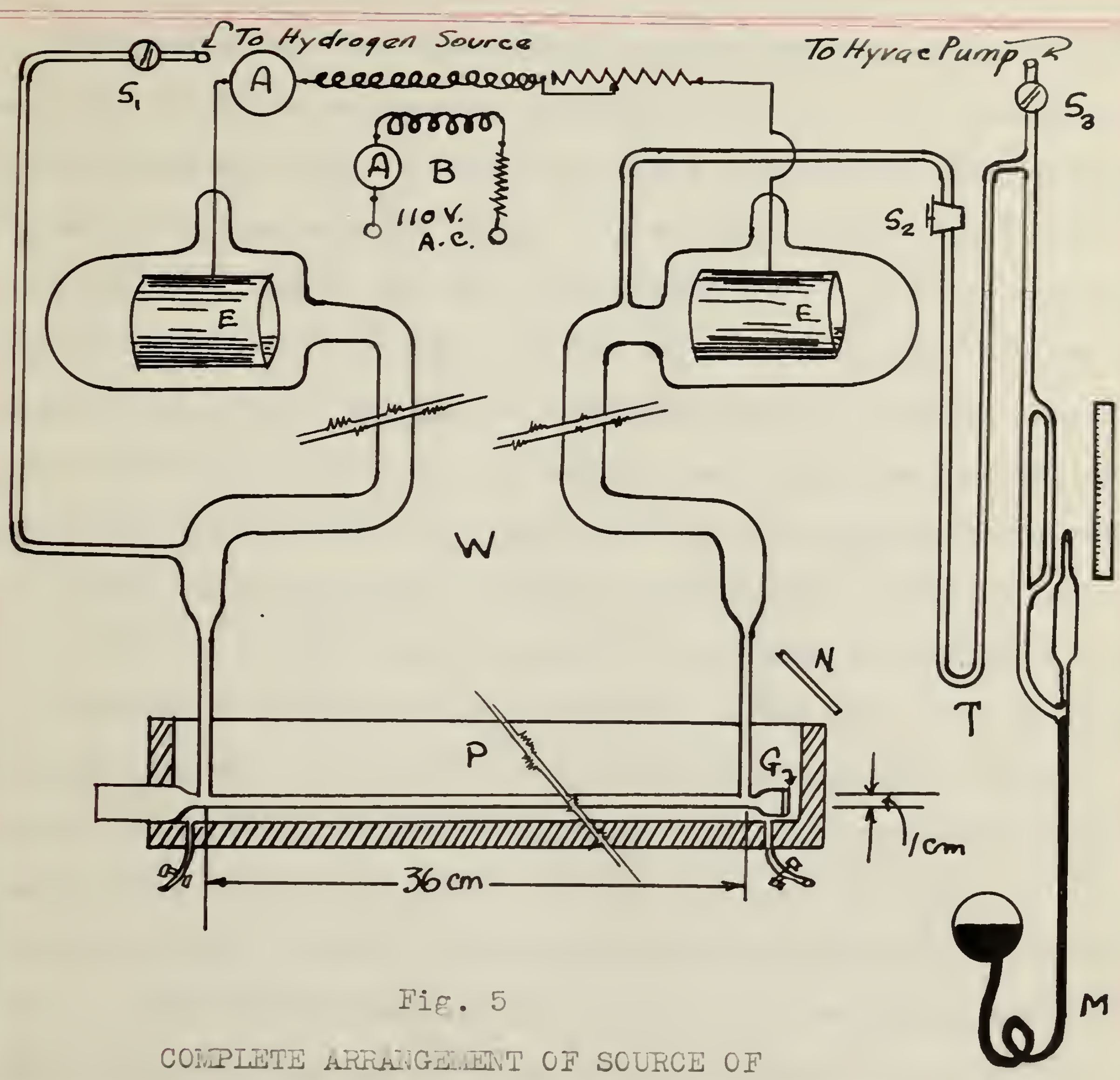

Fig. 5

COMPLETE ARRANGEMENT OF SOURCE OF

RADIATION

W - Wood Tube

T - Mercury Trap (Liquid air cooled)

M - McLeod Gauge

G - Mirror

N - Mirror for viewing height of liquid air around capillary

E - Aluminum electrodes

S_1, S_2 and S_3 - Stop-cocks

B - High voltage Transformer

P - Pine wood block used as liquid air trough

The center of the tube exhibits the Balmer series, with the secondary spectrum reduced to 1/50 of its usual intensity when the pressure was held at or below such a value that the positive column striations were evident. The secondary spectrum is due to molecular hydrogen and the Balmer spectrum to that of atomic hydrogen. With a very weak current the secondary spectrum is fairly strong while the Balmer lines are weak or absent. Increase of current strength weakens the secondary spectrum which passes through a minimum of intensity; as the current increases the Balmer lines increase steadily in intensity. This is due to the fact that molecular hydrogen is reformed as rapidly as it is broken down into atomic hydrogen, in the case of a feeble exciting current. As the current strength increases, the proportion of atomic hydrogen becomes greater, the secondary spectrum becomes relatively weaker and the Balmer lines become stronger. This, however, does not go on indefinitely, for presently, with further increase of current, the secondary spectrum begins to brighten and both spectra increase in intensity at about the same rate. Then by producing a higher vacuum the secondary begins to weaken and falls to about 1/50 of its original intensity. Visual observation shows that the width of the lines decreases with decreasing current density. Since, according to Wood[1], the potential applied to the tube is always sufficient to dissociate the hydrogen, the walls of the tube and the

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[1] Wood, R. W., Roy. Soc. Proc. A 97, 455 (1920).

electrodes act as a catalyser, and almost instantaneously change the atomic hydrogen back into molecular hydrogen; then a high vacuum must be maintained to offset this reaction if the Balmer lines are to be strong.

SPECTROSCOPIC SYSTEM

A diagrammatic sketch of the spectroscopic system is shown in Fig. 6, page 26. Two Lummer plates are used in tandem. The first Lummer plate, L_1, with a thickness of 0.4827 cm, length 13.1 cm, and width 1.45 cm is placed on a specially constructed holder which has three legs. This holder rests upon the platform of a Hilger constant deviation spectroscope constructed especially for it. The Lummer plate L_1, disperses horizontally, and is so mounted that it could be moved about a vertical axis through very small horizontal distances. Only one beam from L_1 was used, the other being cut off by a screen 'O'.

In place of the constant deviation prism a plane reflection grating was used in order to get a straight line pattern of the $H\alpha$ line coming from the Lummer plate L_1.

A shutter[1] was used as an auxiliary slit at the point S_2, (Fig.6) of the second spectroscope. This spectroscope held the large Lummer plate, L_2, which has a thickness of 0.9963 cm, a length of 30.0 cm, and width of 3.98 cm. This plate was placed in a specially constructed case of brass with holes at the top where the temperature could be taken, and was arranged so that

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[1] Originated by Dr. N. A. Kent, (1936), See page 27.

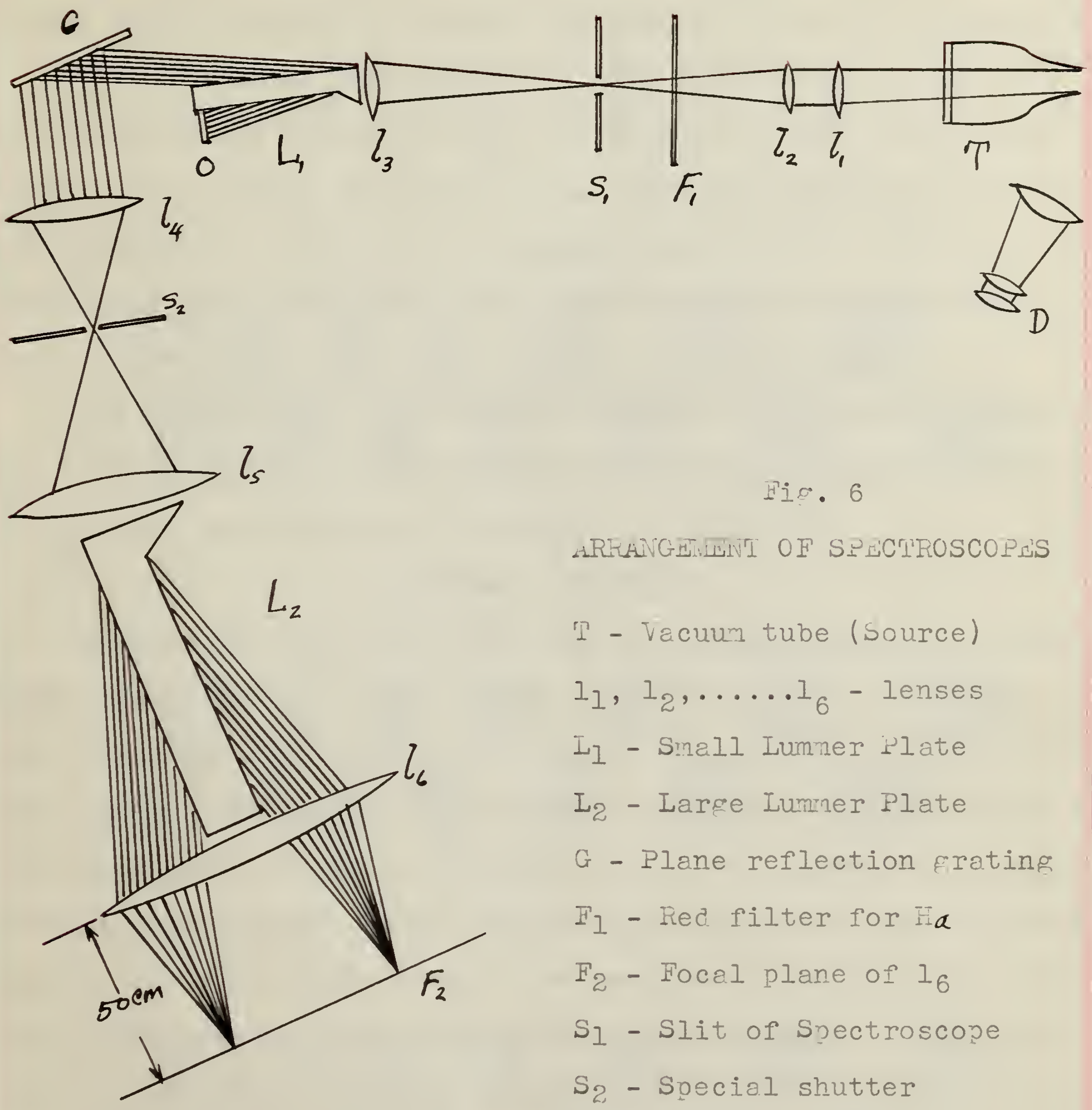

Fig. 6

ARRANGEMENT OF SPECTROSCOPES

T - Vacuum tube (Source)

l_1, l_2,......l_6 - lenses

L_1 - Small Lummer Plate

L_2 - Large Lummer Plate

G - Plane reflection grating

F_1 - Red filter for H_α

F_2 - Focal plane of l_6

S_1 - Slit of Spectroscope

S_2 - Special shutter

D - Direct vision spectroscope

O - Opaque screen

it dispersed horizontally also. At the focal plane of lens 6, is the camera box and an ocular for viewing the pattern visually.

The light from the end of the tube was passed through a H. R. Pyrometer red filter of pyrex glass 53% No. 241 and 4.37 mm thick. This filter isolated the H_{α} line eliminating all extraneous light. Lens l_6 is a compound monochromat, made by Bausch and Lamb, the field being flat to within a small fraction of a mm over a central region 5 cm in diameter.

The photographic plates used were especially made by Eastman Kodak Co., for exposure in the H_{α} region. They are known as No.144-F and developed by Eastman formula D-19.

AUXILIARY SHUTTER

In place of the usual slit used on the spectroscope of the large Lummer plate, a shutter was constructed that had alternate black and clear spaces on a piece of lantern slide glass. This shutter was made by photographing the pattern produced by the small Lummer plate at the focus S_2 of the telescope of the grating spectroscope. This photographic plate was then developed, and the region which was to be used magnified 50 times and again photographed on a large piece of photographic paper. On this positive were pasted black and white strips of paper covering alternately parts of the two components of the main line as shown in Fig. 8, page 28. This was then rephotographed and reduced to the normal size on a lantern slide. When this shutter was placed as the slit on the spectroscope of the large Lummer plate and illuminated, a pattern was obtained as shown in Fig.9.

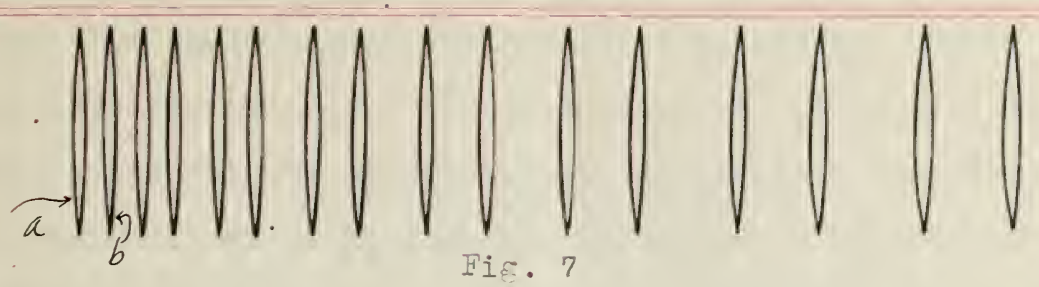

Fig. 7

Pattern given by small Lummer plate, (a) one component, (b) the other component of the doublet.

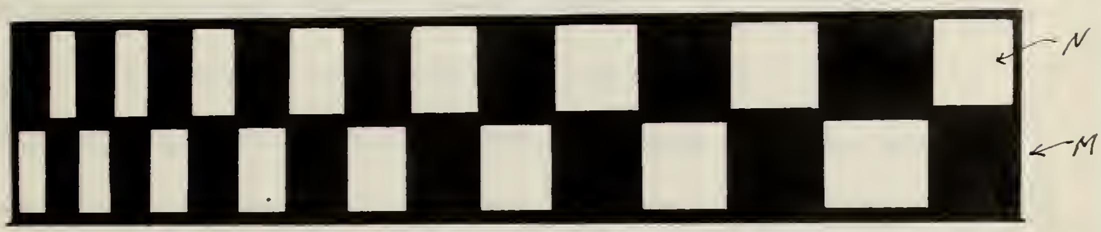

Fig. 8

'M' black strips of paper and 'N' white strips of paper pasted on enlarged photograph of the H_α pattern.

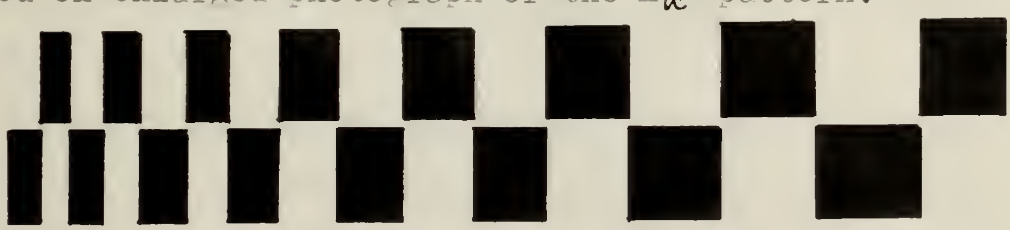

Fig. 9

Pattern obtained without either Lummer plate. This is called the shutter.

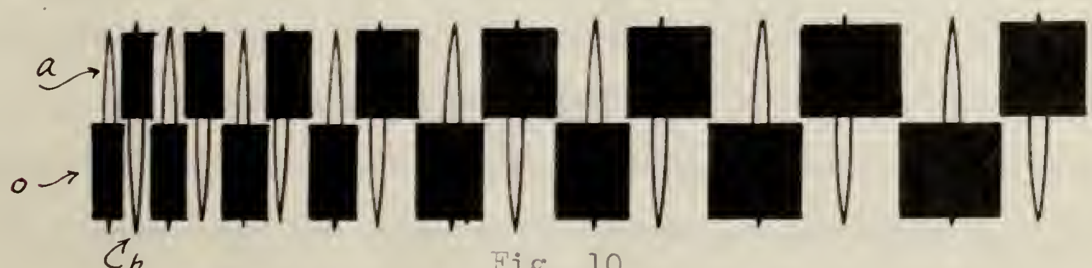

Fig. 10

Shutter shown on pattern formed by small Lummer plate. 'a' one component, 'b' other component, 'O' opaque region.

If, then, the small Lummer plate was put in and H_α thrown upon the shutter, one component of the doublet was admitted through at the top and cut out at the bottom, alternately throughout the entire region as shown in Fig. 10, page 28. 'a' represents one component of the doublet, 'b' the other component and 'O' the black space due to the shutter, so that either a left or right component would be free for photographing. This will be discussed more fully under experimental procedure.

TEMPERATURE AND VIBRATION CONTROL OF THE OPTICAL SYSTEM

To obtain full resolving power and constant patterns of a well constructed Lummer plate, the surface must be clean and free from grease and the plate must be at a constant temperature; also vibrations cause the pattern to shift on the auxiliary shutter.

To eliminate the latter difficulty, the entire optical system was placed upon a concrete table four inches thick and having four concrete and brick legs each measuring twelve by twenty-two inches, imbedded in sawdust.

In order to keep the temperature of the Lummer plates constant, the whole spectroscopic system was enclosed in a double walled casing made of building paper; and a heating circuit was constructed as shown in Fig. 11, page 30. A mercury thermostat R_1 was placed near the side of the large Lummer plate L_2. This operated an electromagnet which controlled the heating circuit. The resistance R was set so that about 0.4 of an ampere flowed through the magnet of relay R_2 when relay R_1 was closed, thereby

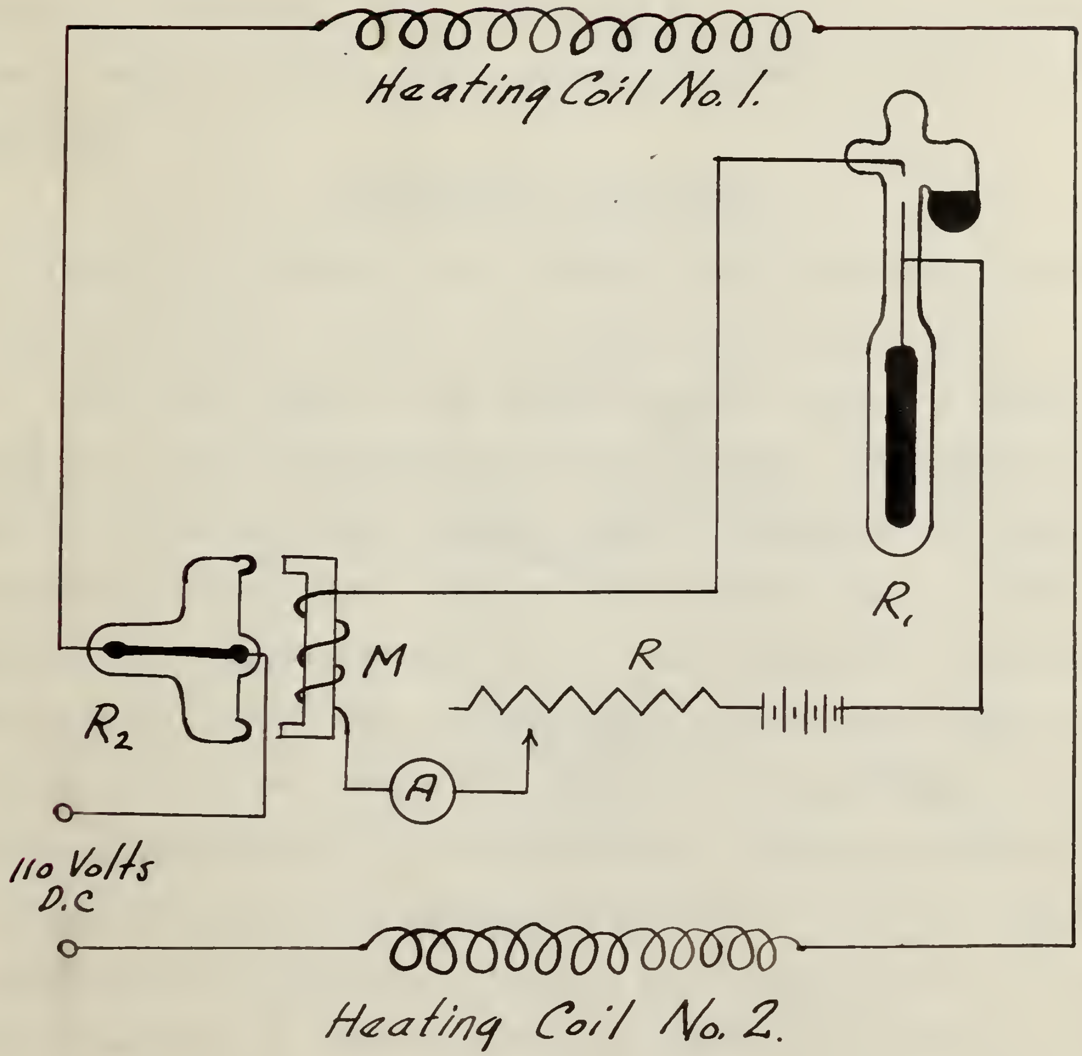

Fig. 11

DIAGRAM OF HEATING CIRCUIT

R_1 - Mercury thermostatic relay

R_2 - Mercury relay magnetically controlled

R - Resistance in circuit

M - Electromagnet

A - Ammeter

causing a positive break of the heating circuit. Relay R_1 was set at 26.7°C. and when the temperature rose to this value it cut off the heating. Thus there was an oscillation of temperature of about 0.1 to 0.5 of a degree throughout a full run or exposure.[1]

EXPERIMENTAL PROCEDURE

The usual procedure was followed in lining up the spectroscopic system and focussing the slits S_1 and S_2. (Fig. 6, page 26.) The small Lummer plate L_1 was turned through a horizontal distance to give the size of pattern desired. The grating G was rotated by means of the tangent screw attached to the table upon which it rested until the pattern entered lens l_4. Both the grating and the Lummer plate had to be readjusted alternately several times until the maximum intensity for that particular size of pattern was obtained. Finally the grating was adjusted for perpendicularity in both directions. With conditions of greatest efficiency and maximum intensity of both the small Lummer plate and grating, attention was then directed to adjusting the shutter to fit this size of pattern for which it was originally designed. The shutter was moved horizontally by screw 'a' and through an angle about a horizontal line by means of screw 'c' and 'd'. Fig. 12, page 32. After it was arranged so as to free one component at the bottom and eliminate it at the top it was fastened in place by means of screw 'e'. Then

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[1] This sytem was however not used, because the temperature remained almost constant without it.

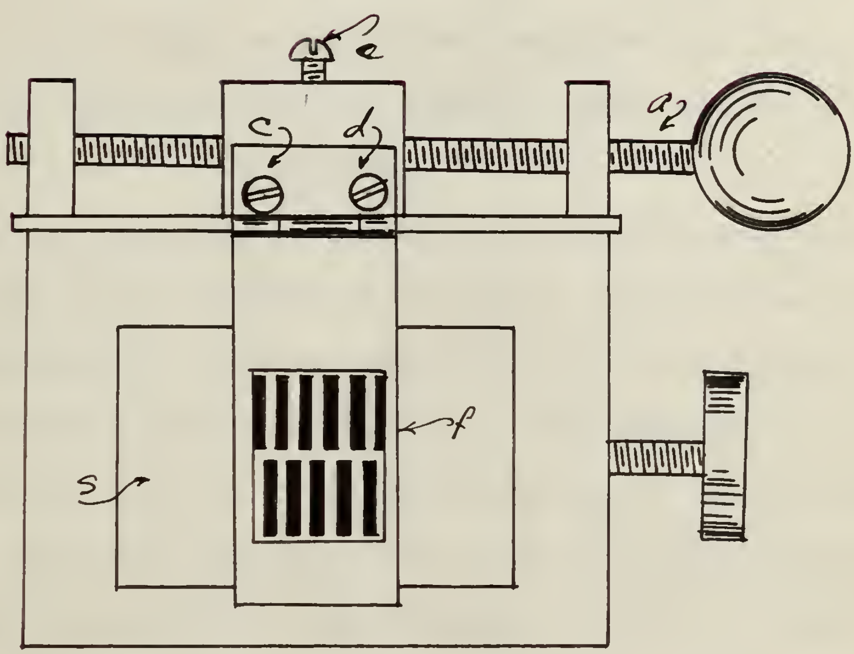

Fig. 12

SHUTTER HOLDER

a, c, d and e are adjusting screws

f - Shutter

s - Slit jaws

the telescope and plate holder of the large Lummer plate was shifted over to the correct position and clamped. The small Lummer plate was so sensitive to temperature changes that adjustments had to be made before each exposure.

The shutter and the H_α pattern had to be parallel to the vertical face of the big Lummer plate, else the pattern given by the latter would contain patches of lines that decreased in height and intensity. This is shown in photograph No.L2-13.

OPERATIONS FOR PHOTOGRAPHING THE PATTERN UNDER LIQUID AIR CONDITIONS

The current in the secondary circuit was maintained constant and the capillary submerged in liquid air during an exposure. The pressure was held at about 0.11 mm of mercury with the secondary spectrum almost eliminated. The spectrum was observed constantly by means of a constant deviation spectroscope to see that the secondary spectrum was of very low intensity. The time of exposure, pressure and secondary current varied for different plates as can be seen on examining Table III. The red filter as previously described was used on all exposures and the time of developing the plates varied from six to five minutes.

The liquid air tube was made out of a block of light pine wood, the inside being hollowed out so that there was about 1 cm clearance around the capillary and the window of the tube projected at the end about 3 cm. The entire block was covered with a coating of glyptol thereby adding to the efficiency of

the cooling system and at the same time saving in the use of liquid air.

COMPILING OF DATA AND PHOTOGRAPHS

Discussion

Table III gives plates that are shown in enlarged photographs on pages 36-40. Plate L2-4 shows the pattern produced by the small Lummer plate. The separation of the doublet is clearly seen. This plate was used to make shutter No.1. Shutter No.2 was made from a similar pattern produced by the small Lummer plate, but a larger pattern was used. Plate L2-7 compared with L1-12 and L2-13 shows the presence of more groups due to the different size of shutters and L2-13 also illustrates the effect obtained when the shutter is not parallel with the pattern formed by the small Lummer plate. L2-15 shows visually the doubling effect produced by the system. Below, the left component is free and above, the right component is free. On L1-17, the shorter λ' is unmasked below. On the right hand pattern at the top there appears to be a third component. However, this is not an Al plate because the shutter is not in the correct position.

In L2-18, the shorter λ' is unmasked above, and longer λ'' below appears to have structure at the left of the right group. The patterns are well marked and separated. There is seen visually asymmetry to the right for group two. This shows distinctly that λ' gives one group of lines in larger Lummer plate and λ'' gives another group of lines. This appearance of

TABLE III

Date	Plate No.	Current ma/cm^2	Exposure time	Vacuum (mm of Hg)	Character of spectrum	Shutter No.
1/11	L2-4	26.0	25 sec.	.10	medium	none
1/27	L2-7	26.0	40 min.	.10	heavy	1
3/9	L1-12	26.0	40 "	.10	faint	2
3/29	L2-15	27.0	56 "	.10	medium	2
3/9	L2-13	29.0	40 "	.10	heavy	2
4/2	L1-17	30.0	41 "	.11	faint	2
4/2	L2-18	30.0	40 "	.12	medium	2
4/2	L3-19	40.0	24 "	.10	faint	none
4/5	L2-20	32.0	4 "	.10	heavy	"
4/6	L2-23	33.0	74 "	.10	medium	2
4/13	L3-26	29.0	68 "	.14	medium	none*

TABULATION OF PLATES

All plates taken with liquid air except L2-4.

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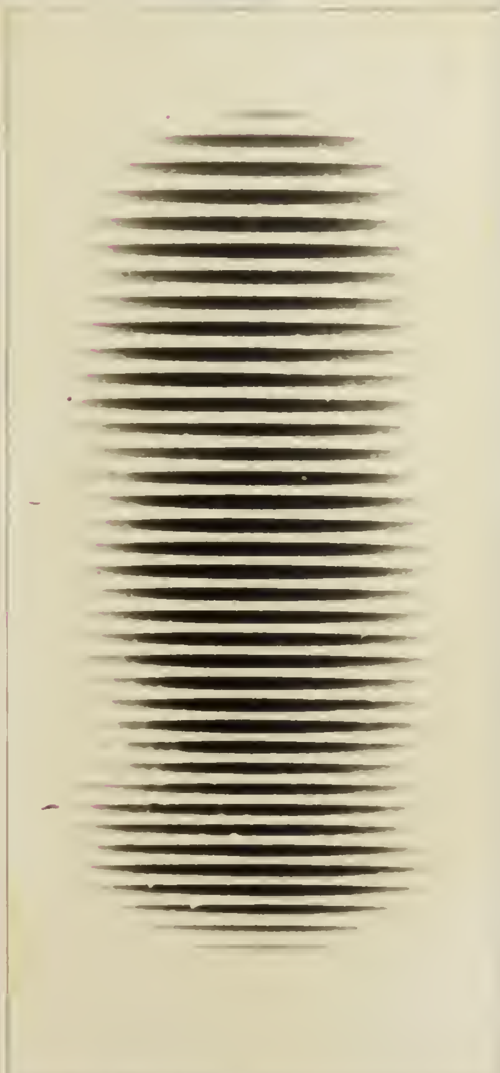
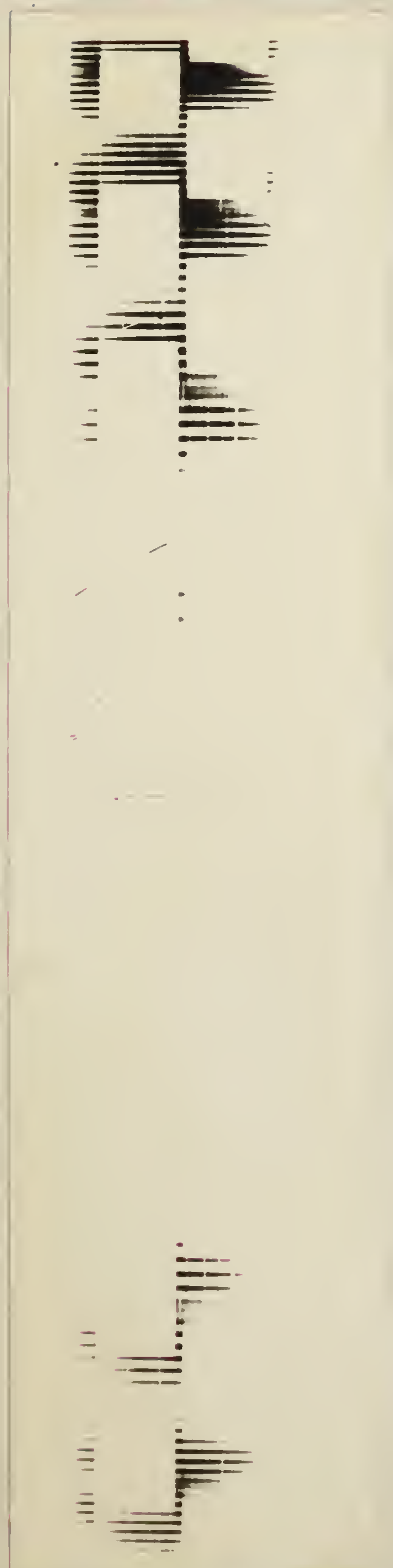
* L3-26 was made with the mirror substituted for the grating.

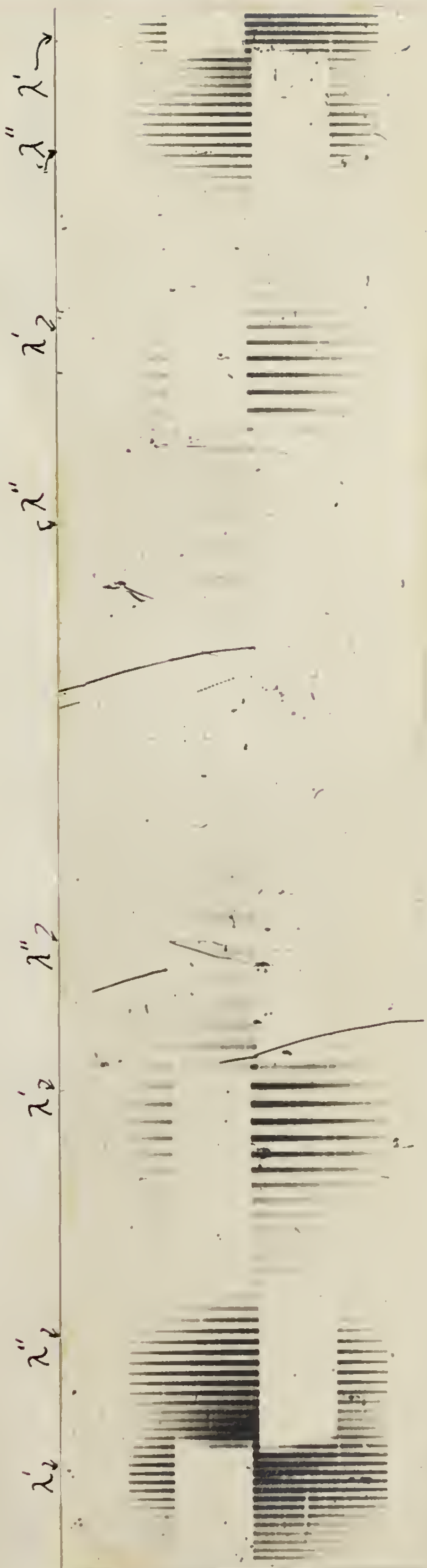


L2-4

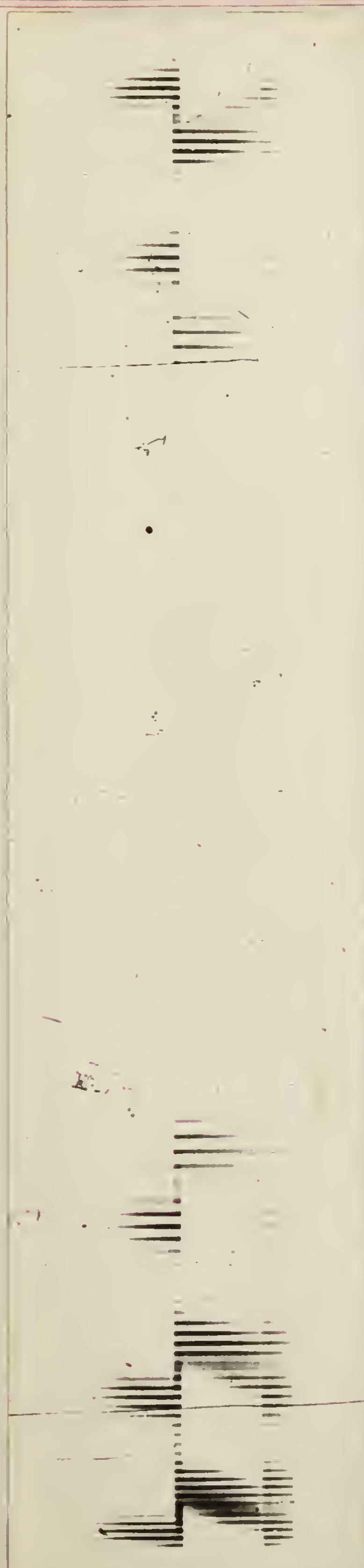
L2-7



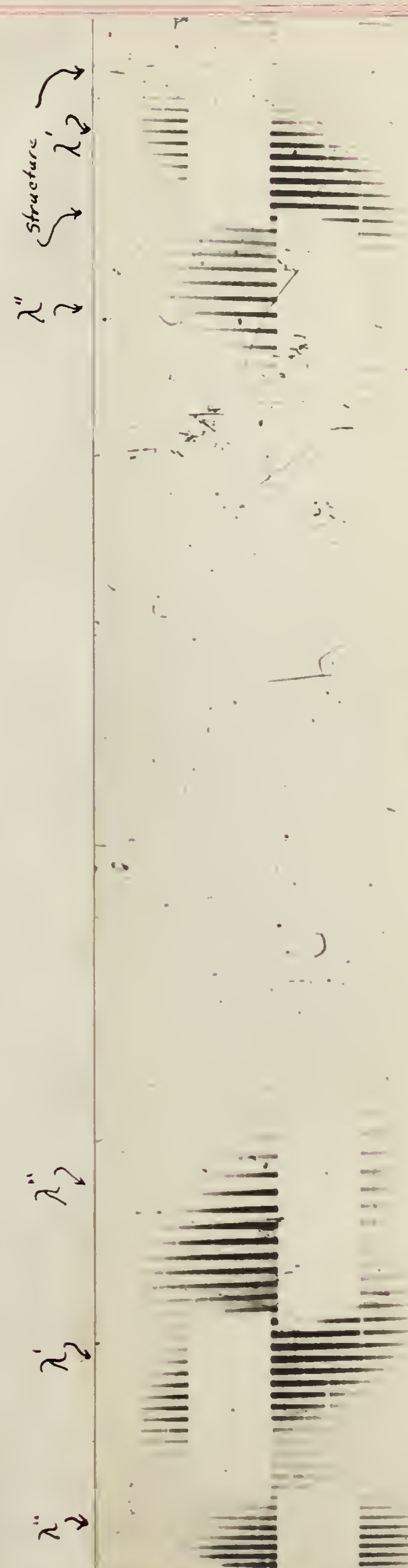
L1-12



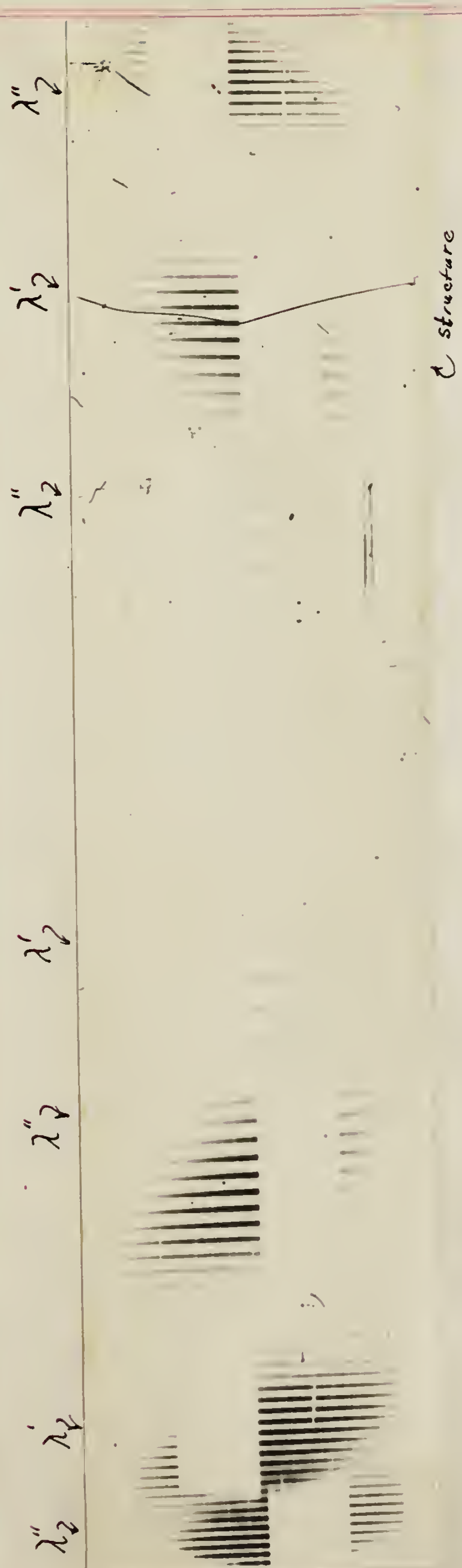
L2-15



L2-13

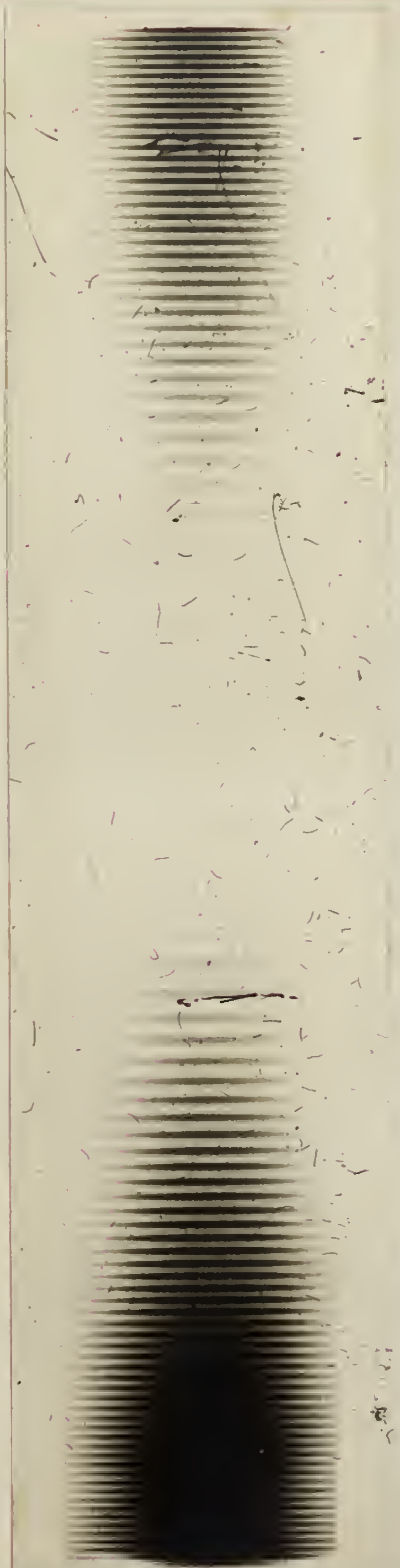


L1-17

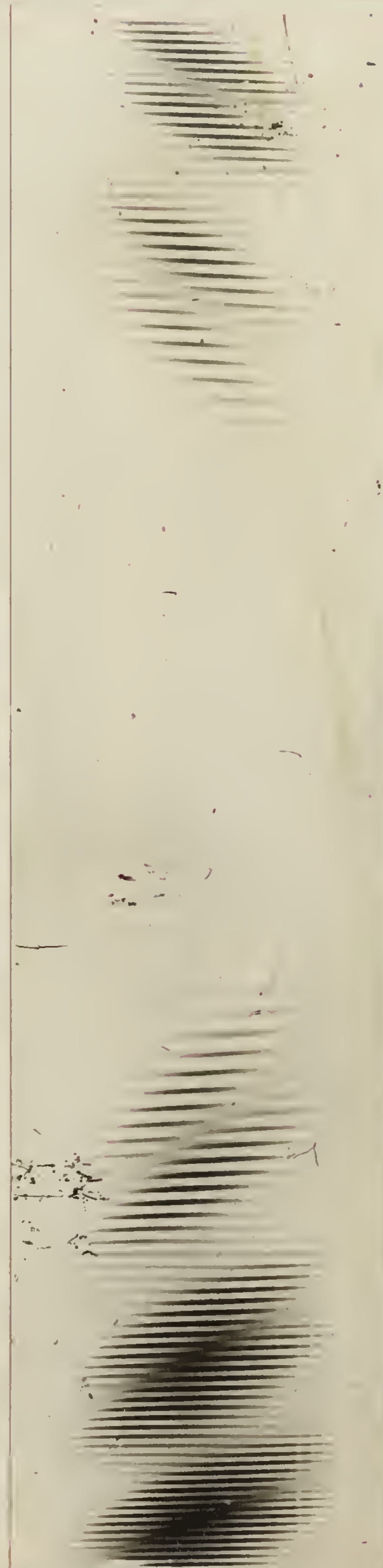


L2-18

L3-19



L2-20



L2-23

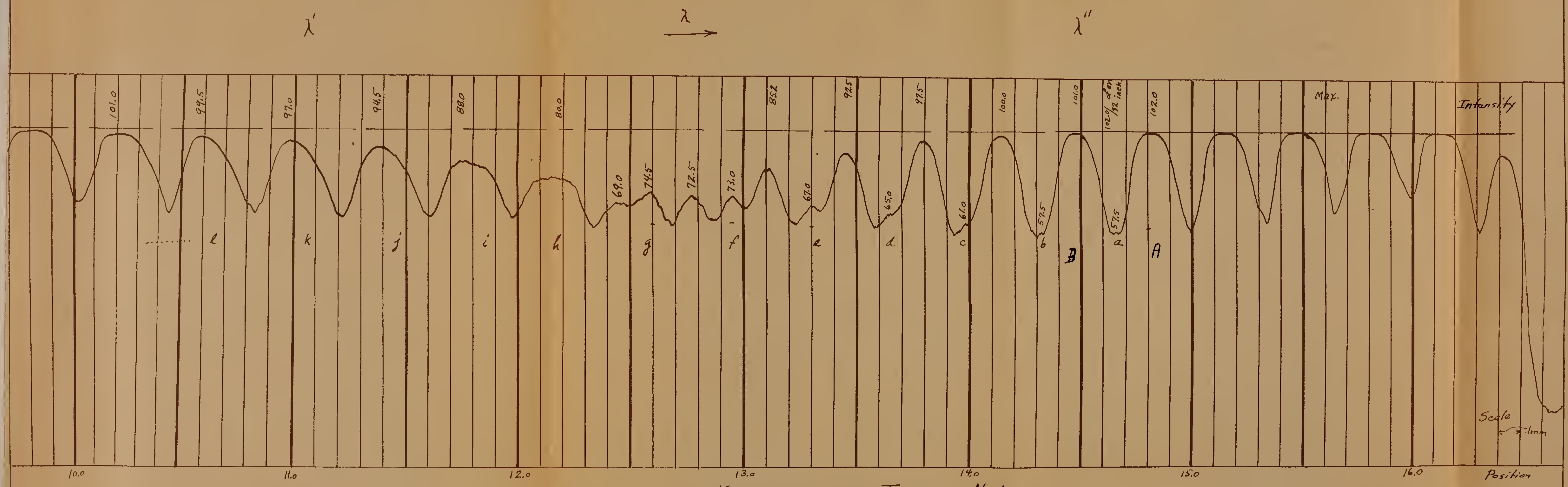
the groups being formed at the top of the pattern where there was no shutter inspired the photographing of L3-19 without the shutter, and the grouping appeared as alluded to above.

L2-23 illustrates the effect produced when the two patterns are at a slight angle with each other. A partial ring system is formed. L2-20 is taken without the small Lummer plate and shows clearly the breadth of the lines, which is a very good indication that the component of one order overlaps the main fringe of the next order giving definite proof that the large Lummer plate could not be used alone.

MICROPHOTOMETER CURVES

The microphotometer curves shown on pages 42 and 43 are an exact tracing of the photographic negatives produced at the Jefferson laboratories from plates L2-7 and L3-26 respectively. The slit of the microphotometer ran along the region marked a-b at the top of the plate L2-7, a region in which the shutter was not present. This same structure is observed at other corresponding places on the plate, but with insufficient density to give a good curve. On L3-26 the slit ran from the center covering λ_1'', λ_1', and λ''_2.

As has been explained before, the shorter wave length λ' appears in a series of orders in the pattern of the larger Lummer plate, similarly with λ'' the longer wave-length component of the doublet. Point 'A' marks on tracing No.1 the maximum intensity of the λ'' group, the intensity of the different orders falling off in both directions, that to the right not ap-

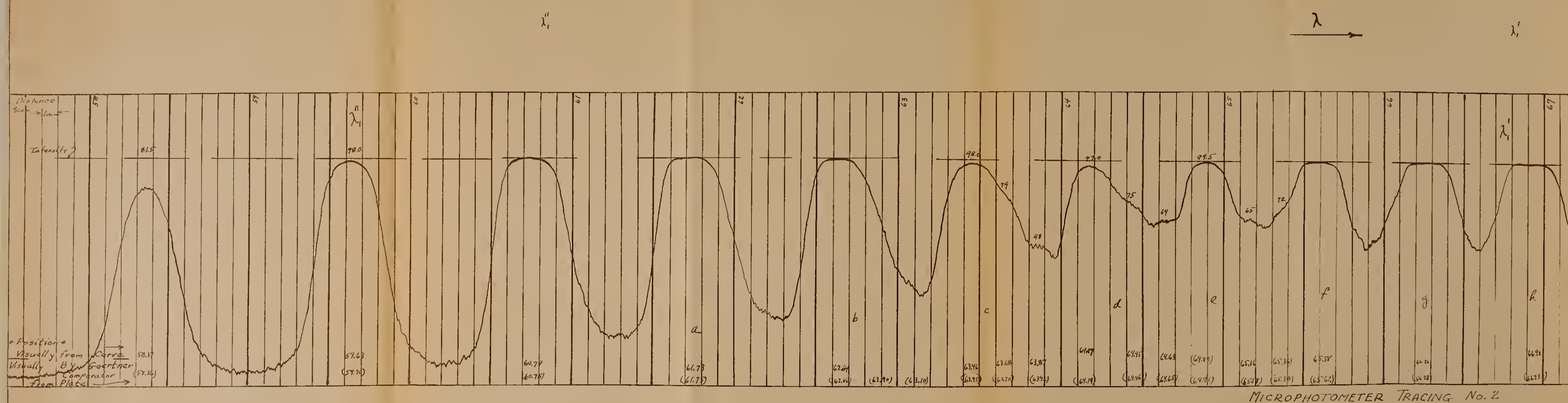


MICROPHOTOMER TRACING No. 1.

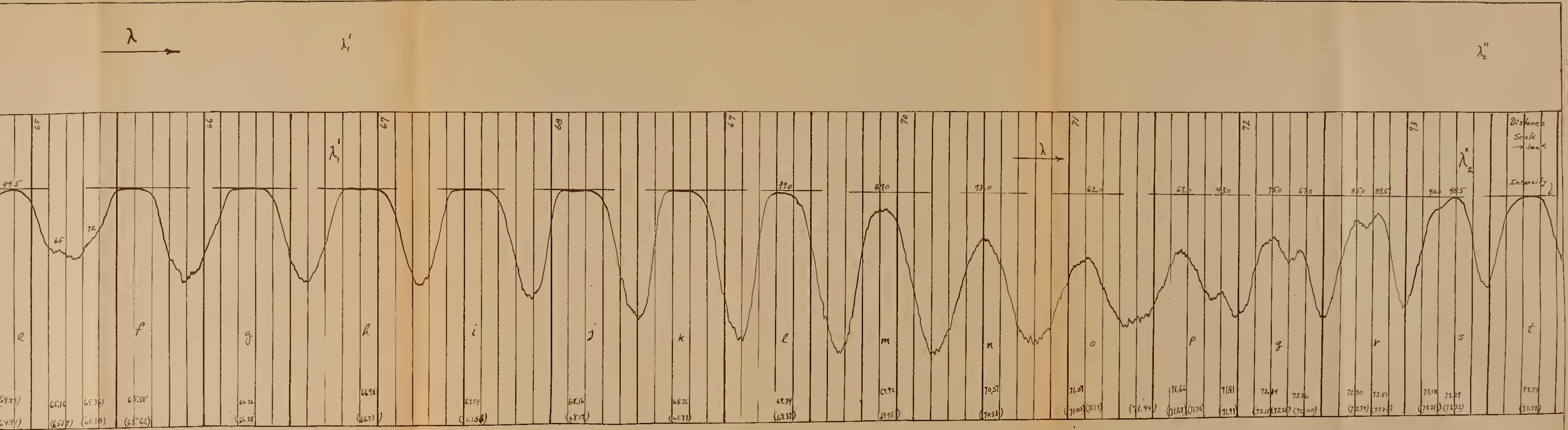
Magnification 80 Times

Microphotometer Curve Made By Dr. Jordon
of Harvard University

Traced By
W.H. Robinson '37.



MICROPHOTOMETER TRACING No. 2
Magnification 80 Times
Microphotometer Curve Made By Dr. Jordon
Of Harvard University.



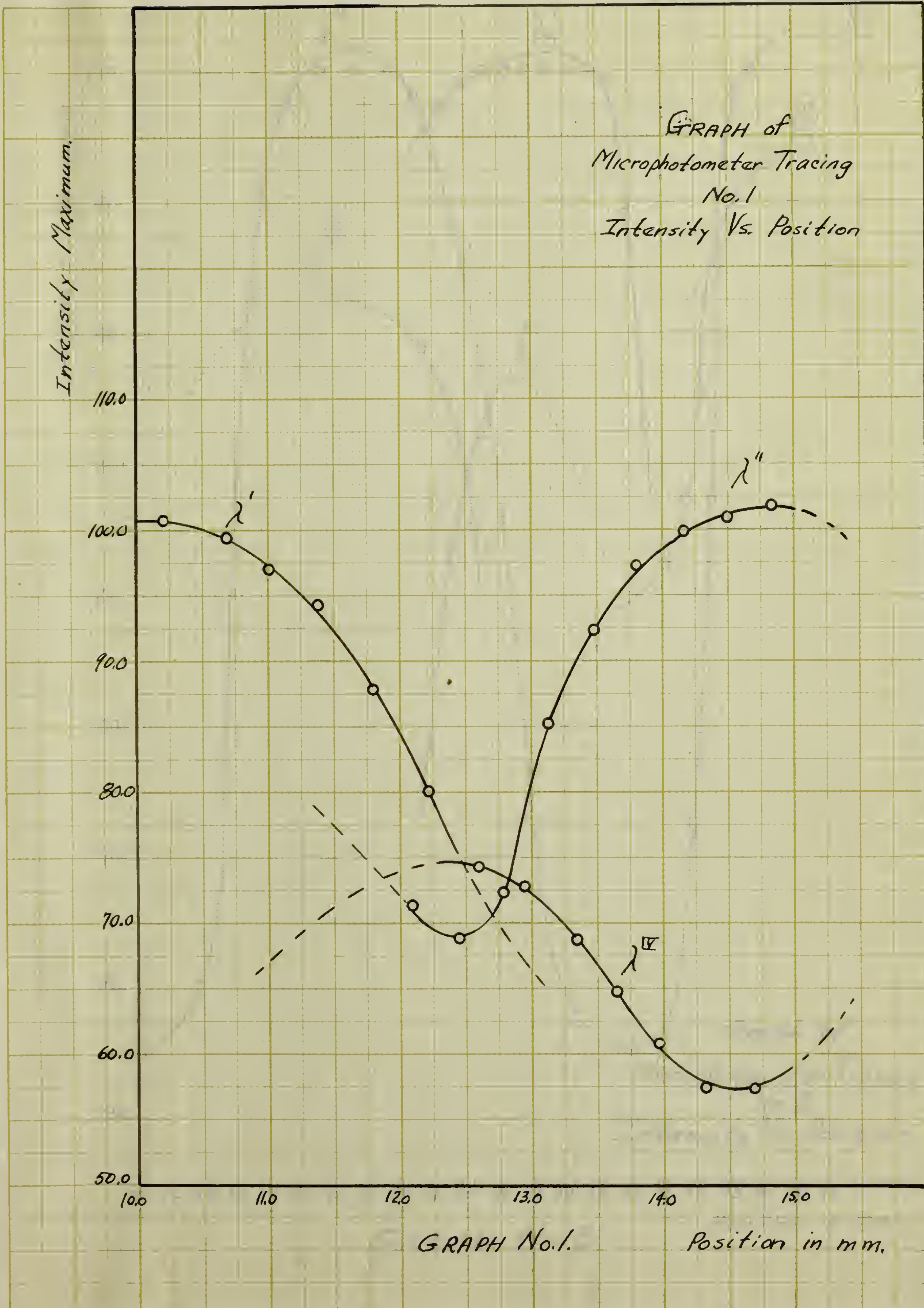
MICROPHOTOMETER TRACING No. 2
Magnification 80 Times
Microphotometer Curve Made By Dr. Jordon
Of Harvard University.

Traced By
William H Robinson '37

pearing because the end of the plate comes too soon.

On microphotometer tracing No.1, the components λ' and λ'' are involved in the region of 'g' to 'l' and probably produce the asymmetry on the right of λ'. The peaks appearing at 'a' and continuing to 'g', omitting peak 72.5, belong to <u>another series</u>. The relative intensities of each line in the groups and the positions of maximum intensities are marked directly on the tracing. From a graph plotted between these quantities (see graph No.1) it is clear that the points fall on <u>three</u> distinct curves; taking into account the relative positions of these three curves, it is evident that it is the λ'''' component which produces the third curve.

Microphotometer tracing No. 2, made from plate L3-26 shows λ''_1, λ'_1, and λ''_2, where the subscript denotes corresponding orders of the first Lummer plate. From point 'a' to 'd', the Lummer plate lines are asymmetric due no doubt to the superposition of λ''' on λ''. At the points 'e' to 'm' there is asymmetry due to the combination of λ''' and λ'; from 'n' to 't' the asymmetry is probably due to the superposition of λ'' and λ''''. The graph of the microphotometer tracing No. 2, shown on graph No.2 shows clearly that there are <u>four</u> distinct curves. By ex-


GRAPH of
Microphotometer Tracing
No. 1
Intensity Vs. Position
Intensity Maximum.
110.0
100.0
90.0
80.0
70.0
60.0
50.0
10.0
11.0
12.0
13.0
14.0
15.0
λ'
λ''
λ^IV
Position in mm.

GRAPH No. 1.

Intensity Maximum
100.
90-
80-
70-
60-
50.
40-
30-
20-
55 56 57 58 59 60 61 62 63 64 65 66 67 68 69 70 71 72 73 74 75 76
Position in mm.
λ''₁
λ'₁
λ''₂
λ^IV₂
λ^IV₁
λ'''₁
Graph of Microphotometer Tracing No. 2. Intensity Vs. Position

GRAPH No. 2.

trapolation the maximum of the component λ'''' lies to the left of λ'' and that of λ''' to the left of λ'. This agrees with the theory. The graph of the components are distinct in themselves, because the measured differences in mm., between maximum peaks in each series bears a definite relationship to that particular series. Therefore the graphs are not continuous as would be expected if no other line entered.

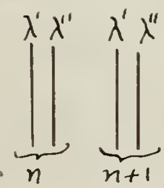
RESULTS

The use of the Lummer plate as an auxiliary spectrograph in series with a larger Lummer plate, both dispersing in the same horizontal plane and a plane reflection grating located between the two Lummers to further disperse the lines, furnishes a means by which the fine structure of H_α can be studied more readily.

In the groups of λ' and λ'' there appear no ghosts, because the Lummers used were free of them. This was to be expected, for Kent, Taylor and Pearson used them in a crossed system and proved experimentally that they were absent. The grating does not possess ghosts of sufficient intensity to appear on the pattern, and furthermore the same pattern was obtained when a plane aluminized mirror was used in place of the grating.

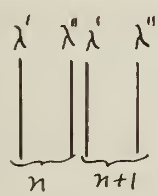
Therefore it can be stated conclusively that this arrangement of the Lummer plates and grating furnishes a very encouraging method for studying the components of the H-alpha doublet and any other line of composite nature. Since this method has now been opened up for studying fine structure in this manner,

there are some improvements which may be as worthy of being tried out. First, the light from the discharge tube could be passed through a constant deviation prism and the light from the line selected passed through the small Lummer plate spectrograph and the final pattern obtained from the large Lummer plate spectrograph. Finally the two plates might be set one behind the other in one spectrograph, thus eliminating two lenses. Further, if the small Lummer plate gave a pattern characterized by a greater separation of the components and less separation between the orders it would be easier to search for λ'''. One should thus have instead of



order

the following:-



order

which would give greater separation of the groups formed in the pattern of the larger Lummer plate. The largest orders obtained from the small Lummer plate should be used.

SUMMARY

The greatest impetus to modern physical research came in Bohr's well known theory of the hydrogen atom. Although this theory broke down in its details, when applied to the heavier elements, it yielded, with Sommerfeld's modification, good quantitative agreement with all experimental observations of hydrogen itself. The quantitative feature of Sommerfeld-Unsöld's

modified form of the Bohr theory, which involves the resolution of apparent single lines into several 'fine structure' components was thought at one time never to be tested adequately for hydrogen—— due to overlapping and blurring of the component lines caused by the high velocity of hydrogen atoms moving in the region of the excited discharge (Doppler effect). Simple gas kinetic theory indicates that the atomic velocities and hence the blurring should be less with deuterium than with ordinary hydrogen and therefore more easily resolved because of the smaller Doppler effect for the heavier atom. Thus, the recent investigators have turned to deuterium rather than ordinary hydrogen to test the fine structure theory of hydrogen.

Not completely satisfied that a better method could not be found for studying the fine structure of ordinary hydrogen, Dr. Kent presented the idea to me —— that I should study the spectrum with the Lummer plate as an auxiliary spectrograph in series with a larger Lummer plate. Since this had never been done, this study was made and the results showed surprising possibilities for obtaining fine structure of this line and furthermore opened up a larger field of hyperfine structure of the lines of other elements.

One important advantage of this system is that greater dispersion is obtained since both instruments are dispersing in a horizontal plane. As a result one line of the doublet formed by the small Lummer plate gave one group of lines in the larger Lummer plate pattern and the other line of the doublet gave an-

other group. Hence both components could be studied separately even without the use of the shutter.

A further advantage of this system is that the pattern formed is composed of straight lines and therefore a long and narrow microphotometer slit could be used. Therefore the microphotometer curves obtained are composed of smooth lines and no approximations are necessary to correct for plate grain or irregular curves.

In conclusion we feel justified in stating that the study of the H-alpha line by using a Lummer plate as an auxiliary spectrograph in tandem with a larger Lummer plate offers tremendous possibilities of studying the third component of the doublet with a possibility of even showing the fourth under improved conditions.

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Born March 3, 1900 in Louisville, Kentucky. Son of Amanda Obannon and Lee Robinson. Received elementary education at the Washington Street grade school, and high school education at Central High school, both in Louisville. Graduated from the engineering school of the University of Pittsburgh, Pittsburgh, Pa., in 1922 with the degree of B.S. in E.E., and from the graduate school of Boston University, Boston, Mass., in 1933 with the A.M., degree. Married Mabel L. Leverett September 18, 1924 and held the following teaching positions:- Assistant Director of Mechanic Arts at Prairie View State College, Prairie View, Texas; instructor in mathematics and physics at Brick Junior College, Bricks, N.C.; at present, professor of mathematics and physics at Tillotson College, Austin, Texas. Member of the Alpha Phi Alpha fraternity.